

Hyperloop – an Innovation for Global Transportation?

Dr. Josef Doppelbauer, Valenciennes

Since its announcement by Elon Musk in 2013, regular reports appear on the proposed novel system for ground transportation “Hyperloop” – a system based on transport containers (“pods”) that are shot point-to-point at speeds above 1000 kph through a quasi-evacuated tube. This article intends to discuss a number of basic questions on the Hyperloop system and its practical application, in addition, some fundamental aspects related to innovation in (infrastructure) networks shall be discussed as well.

1. Introduction

Over a press conference in August 2013, the South African-born and world-wide active entrepreneur Elon Musk (founder of PayPal, SpaceX, Tesla, ...) proposed, under the designation “Hyperloop” a novel transportation system, and described it in detail in a concept paper [1]. It is remarkable that Musk does not ask for any license fees on the proposed concept (“open source” concept) – therefore, since 2013 a number of private enterprises have been established for the development and marketing of Hyperloop-based systems [2 – 3].

The basic idea behind Hyperloop is that, similar to pneumatic Mail [], capsules/pods are shot at high speed (> 1000 km/h) through an (almost) evacuated tube. Obviously, this is a form of public transport as Hyperloop needs special vehicles in a specially built infrastructure. Application of Hyperloop is foreseen for both passengers and freight [] transport.

Since the first publication Hyperloop is surrounded by a collection of myths, ranging from science fiction to envisaging an all-encompassing solution for all transit problems in the world.

With this article it is intended, on the one hand, to make a community of readers from mainly the railway sector acquainted with the essential facts of Hyperloop, on the other hand to distill the key questions that demand serious clarification prior to any realization of Hyperloop. It is not the intention of this article to challenge Hyperloop – on the contrary, it is up to the promoters of Hyperloop to convince potential investors, public institutions and government officials, and eventually potential customers that Hyperloop may be a safe, efficient and economic way to meet mobility needs.

It should be remarked here that guided transport systems such as Hyperloop are per se NOT in the scope of activities of the European Union Agency for Railway (ERA). However, the Agency per its regulation shall contribute to railway related research and promote innovation. In any case innovation is fostered by the competition of ideas – the author therefore welcomes any proposal how public transport can be made more attractive and the transport system as a whole can be made more sustainable.

The approach followed in the context of Hyperloop to organize public challenges for the solution of key problems – for example for finding the most suitable routes for Hyperloop [4] or the so-called „pod competition“ in which various concepts for Hyperloop vehicles compete with each other [5] – could certainly be advantageous in other sectors as well.

2. Physical and technical basics of Hyperloop

The basic idea behind Hyperloop is to practically eliminate the air drag on an earth-bound vehicle by moving this vehicle under reduced air pressure (in a quasi-vacuum at around 100 Pa pressure¹) almost friction-free in a tube (see Fig. 1). Thereby higher speed (target: 1200 km/h) and rather short travel times should be achieved (see Table 1 – the values given do not include the time needed for both loading and unloading the vehicle (pod), Elon Musk assumes 5 min each).

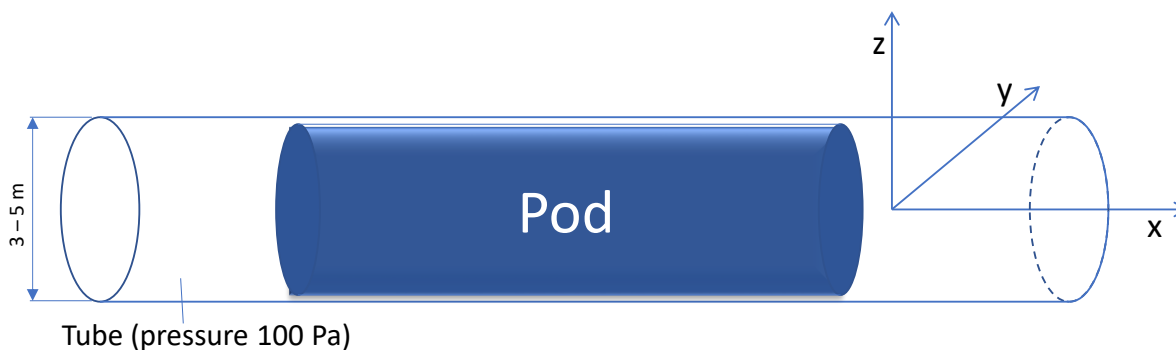


Figure 1: Operating principle of Hyperloop: a transport container („pod“) moves in a tube in near-vacuum (100 Pa)

Connection	Distance (km)	Time in Tube (min)
Bratislava - Vienna	55	5
Dubai – Abu Dhabi	130	9
Helsinki - Stockholm	400	22
Los Angeles – San Francisco	560	30

Table 1: Expected travel time (net) in the Hyperloop tube for typical hypothetical Hyperloop connections (maximum speed 1200 km/h)

One could summarize as follows: **Hyperloop is a horizontal elevator, with acceleration like a rocket, but without intermediary stops!**

In order to investigate the essential features and the key parameters of a Hyperloop system it is sufficient to consider a simplified model on the basis of Newtonian mechanics. As shown in Fig.2, the vehicle is first accelerated until it reaches cruising speed, then it coasts practically friction free (due to the low air pressure, see Table 2), until, in the final phase of the trip, it is braked to standstill.

¹ 1 Pa = 1 N/m² - normal atmospheric pressure is 101 325 Pa = 1013,25 hPa

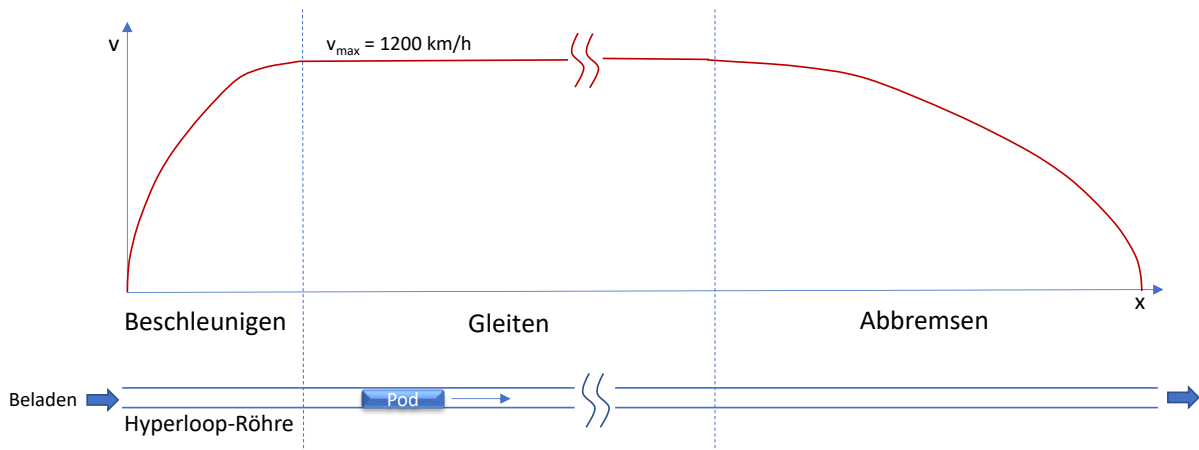


Figure 2: Simplified model of Hyperloop operation and speed (v) – distance (x) diagram

For the acceleration phase, realistic values of the linear acceleration are in the range between 0,5 g und 5 g², linear deceleration values in the range from 0,1 g to 0,2 g appear realistic for the braking/deceleration phase (some comparative values are listed in Table 2). Studies performed by NASA [6] found that a healthy human being is able to tolerate/sustain a horizontal acceleration of 3 g for 25 seconds.

Situation	Acceleration (g)
Car (in 5 s to 100 km/h)	0,5
Saturn V Rocket	1,2
Space shuttle	3
ICE, brake	- 0,05 g (-0,5 ms ⁻²)
Transrapid, brake	- 0,1
Formula 1, dry road	- 0,8
Air drag at 100 Pa (1200 km/h)	- 10 ⁻⁴
Air drag at atmospheric pressure	- 0,8

Table 2: Typical values for acceleration and deceleration

Hyperloop's design parameters are not yet determined, however, one may realistically expect parameter ranges such as indicated in Table 3. For example at an acceleration of 1 g the vehicle in slightly more than half a minute can be accelerated over a distance of 5,7 km to 1200 km/h – the power needed is just below 40 MW (the mass of the vehicle, including 40 passengers, is estimated at

² 1 g = 9,81 ms⁻² (gravitational acceleration)

24 t). Please note that for braking from 1200 km/h to standstill, enormous amounts of energy need to be dissipated (and, of course, kept away from the passengers) – at 24 t vehicle mass the kinetic energy at 1200 km/h amounts to 370 kWh (in t TNT?). The time needed for braking is longer than for acceleration (for reasons of feasible deceleration values) which makes intermediary stops less attractive.

Acceleration (g)	Distance (km)	Time (min)	Power * (MW)	Deceleration (-g)	Distance (km)	Time (min)
0,5	11,3	1,13	19,6	0,1	56,7	5,67
1	5,7	0,57	39,2	0,15	37,8	3,78
2	2,8	0,28	78,5			
3	1,9	0,19	118			
5	1,1	0,11	196			

Table 3: Typical parameters of a Hyperloop system for the acceleration phase (left) and the braking phase (right). Maximum speed 1200 km/h. *) vehicle mass 24 t

3. Hyperloop Vehicle and Guideway

Size/capacity of a Hyperloop vehicle is quoted to be in the range of 25 to 40 passengers per pod (in order to keep the dimensions of the tube reasonably small space in the vehicle will be limited). Several methods have been proposed for propulsion, in most cases based on linear induction. A significant problem that needs to be resolved in any case, in order to safely operate the system, is controlled braking to standstill, in particular when the vehicle in front is stuck in the tube for unforeseen reasons. One can safely assume light-weight construction of the vehicle, it has to be airtight, on the other hand emergency supply with energy and air needs to be foreseen, as well as easy access to the passengers in case of emergency.

The Hyperloop guideway consists of one airtight tube each per direction (diameter around 5m), the equipment for acceleration, braking (without negative impact on passengers)³, as well as a control system to keep the vehicle safely off the walls of the tube. In addition, the tube has to be pumped to low pressure, and this quasi-vacuum has to be maintained continuously.

As the vehicles are contained within a solid tube, any change of direction is difficult with Hyperloop, in particular to go around e.g. stranded vehicles in the tube. As obviously collisions with the tube wall at 1200 km/h are not tolerable, for reasons of weight, energy, and steering the size of the vehicle is seriously constrained. It is also necessary to avoid curves or gradients of the guideway as much as possible: in order to stay within the comfort level of e.g. an ICE or a Transrapid, lateral acceleration of 0,1 g should not be exceeded, meaning that at a maximum speed of Hyperloop of 1200 km/h the permitted curve radius would be > 100 km.

In general, the time delay between subsequent pods is determined by the braking capability and the safety system. As it cannot be excluded that a Hyperloop vehicle comes to a sudden halt in the tube, e.g. caused by an accident, the vehicles following have to be braked safely. An emergency braking system for braking from 1200 km/h could be feasible with a deceleration of 0,3 g (i.e. double the braking performance of Transrapid) – thereby, a realistic minimum time distance of 2 min between

³ It is remarkable that the railway system in the early steam area had to fight with similar problems: it was possible quite early to develop locomotives capable of reaching higher speed – until the invention of the air pressure brake, braking remained problematic

two subsequent Hyperloop pods travelling in the same direction. Table 2 also shows the air drag at atmospheric pressure (neglecting fluid dynamic effects in the tube): should the tube suddenly be filled with air, the resulting “brake” effect would be $-0,8\text{ g}$, braking in 40 s from 1200 km/h to standstill, with 30 MW of power to be dissipated.

A trip with Hyperloop is by necessity connected with staying in a closed, window-less capsule – this might possibly cause claustrophobic reactions with some passengers; in any case, rescuing passengers eventually locked into the pod in an emergency situation is a serious problem demanding a solution. Presumably, in order to enable rescue operations the tube needs to have security access ports at regular distances.

It is also important to note that operation under extremely low pressure makes it necessary to design complex entry and exit systems, including airlocks for the transition from atmospheric pressure to near vacuum in vice versa, as passengers cannot board the pod in vacuum. In addition, entering and leaving a narrow capsule will possibly take several minutes for all passengers. In order not to further limit the number of passengers per capsule and in order to achieve reasonable headway (which determine the transport capacity of the system), an arrangement that enables parallel loading/unloading of several pods needs to be foreseen.

Already from these short consideration it is obvious that for safe and efficient operation of a Hyperloop system a significant number of specific technical installations will be necessary (see also Fig. 3). Passing through these installations will not only require additional time lost on top of the net travel time in the tube, these will also require space, and incurred cost for design, build, and operation should not be neglected.

In this short overview not all technical aspects could be considered. In relation to the expected cost of a Hyperloop system a rough estimate can be made on the basis of the Maglev system Transrapid. Even if the still necessary development effort for Hyperloop is disregarded, it can be expected that Hyperloop will be significantly more expensive than a Maglev system – additional equipment is required (the airtight tube with rescue system, vacuum system, airlocks, ...), other subsystems will require higher specifications (e.g. the propulsion and braking systems). The comparison with Transrapid shows that Hyperloop not only is a technical challenge, but in particular an enormous commercial challenge.

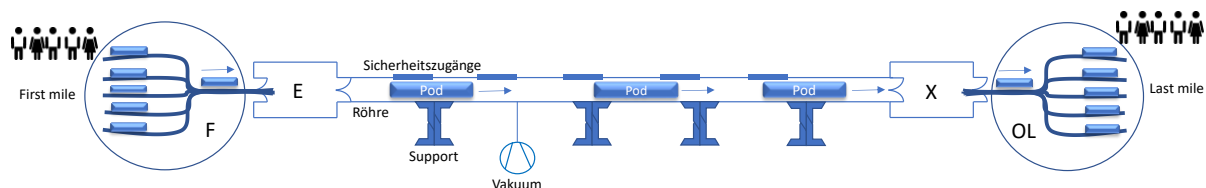


Figure 3: Schematic representation of a Hyperloop system (F: feeder system; OL: offloading system; E, X: airlocks for entry to/exit from the tube; the control command system is not shown in the figure)

4. Hyperloop in Comparison with other Transport Modes

In order to evaluate the benefits of a proposed new transport system the vision of the potential application needs to be considered. Based on the description given in the previous section one has already got the fundamentals for estimating the potential performance of a Hyperloop based system and to benchmark with the key performance data of already existing transport systems.

The key innovation offered by Hyperloop is the expected short travel time – the „price“ to pay for the short travel times envisaged is, as mentioned, that the trajectory of the vehicle must be enclosed (in the tube), which results in complex systems for normal operation and for managing emergency situations.

As geography, position and length of the tube cannot be easily adjusted to actual demand on short notice, Hyperloop is strictly point-to-point. Flexibility of routing is further grossly restricted by the necessity to avoid steep gradients and narrow curves (Figure 4).

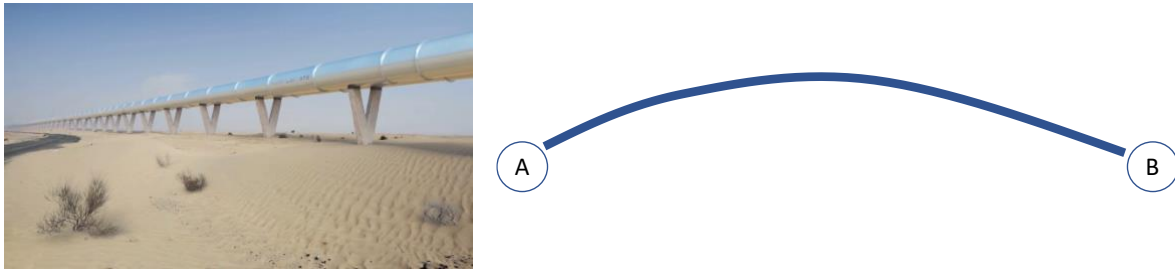


Figure 4: Hyperloop connection A – B (schematic) – the tube is fixed, there are no intermediary stops.

The first use case for Hyperloop, frequently mentioned in publications, is a fast connection over shorter distances of around 50 km, intended for example for connecting two airports. Table 4 shows for this application a comparison of key parameters between Hyperloop, a conventional train, a “people mover”, and of a Maglev system such as Transrapid. In this case, travel times include loading/offloading, the values given for all transport modes considered are to be understood platform to platform (the assumptions for Hyperloop are acceleration 1 g, deceleration – 0,15 g; headway for both train and Maglev is assumed to be 90 s in the best case, for Hyperloop 2 min headway has been assumed).

Interestingly enough, with this application there are no significant advantages for Hyperloop in travel time platform to platform (loading and offloading plus airlocks take their time) – the main problem, however, appears to be the low transport capacity of Hyperloop: even in the best case with fully loaded pods that are shot through the tube in 2 min-sequence only a fraction of the performance is reached of conventional trains or of Maglev. Put differently: a conventional train can transport 1000 passengers from A to B in about 20 min – for the same amount of passengers, Hyperloop needs almost one hour.

	Time ** (min)	Capacity *** (pax per direction and hour)	trains/ pods (both directions)	Cost	Comfort
Hyperloop* (1200 km/h)	14,7	1 200 (40 pax/pod)	24	?	?
Conventional Train (200 km/h)	20,9	40 000 (1000 pax/train)	26	+	++
People Mover/ Rapid Transit (90 km/h)	36,2	35 000 (900 pax/train)	72	+	+
Maglev (500 km/h)	12,3	20 000 (500 pax/train)	14	--	++

Table 4: Travel time and capacity (passengers per hour) for a 50 km point-to-point (e.g. airport – airport) for different transport modes

The values for a distance of 500 km (this corresponds roughly to Los Angeles – San Francisco, Paris – Amsterdam, or to Stockholm – Helsinki) are compiled in Table 5 (here it is assumed that Hyperloop or Maglev can build there stations close to city center, like conventional rail, meaning that this aspect does not differentiate between the modes). The assumptions concerning acceleration and headway are as above.

	Time ** (min)	Capacity *** (pax per direction and hour)	trains/ pods# (both directions)	Cost	Comfort
Hyperloop* (1200 km/h)	37,2	1 200 (40 pax/pod)	46	?	?
High-Speed Train (300 km/h)	107	40 000 (1 000 pax/train)	140	+	++
Maglev (500 km/h)	66,3	20 000 (500 pax/train)	88	--	++

Table 5: Intercity connection over 500 km for different transport modes

In Table 5 one can see a significant time saving with Hyperloop, however, again with significantly lower transport capacity (for the sake of fairness it needs to be mentioned that in current practice high-speed trains operate in 3-min sequence, which means e.g. for Paris – Lyon a maximum capacity of 20 000 passengers per hour and direction). The physical restrictions related to size/maximum number of passengers per pod and to minimum time distance between two subsequent pods imply that capacity will remain a fundamental issue for Hyperloop.

In practice two different application cases of Hyperloop need to be distinguished: applications for which no fast means of mass transport has existed before („green field“) and applications in which Hyperloop shall replace or complement an existing transport system (“brown field“). In both cases it is disadvantageous that with Hyperloop intermediary stops and branches are difficult to implement.

An introduction of Hyperloop in phases, step-by-step, for this reason is not very attractive, in addition, this approach suffers from the fact that (according to Table 3) over shorter distances Hyperloop does not bring any significant advantages. Should, in a brown field situation, Hyperloop need to replace one section of a high-speed train network, meaning that passengers would have to change from train to Hyperloop and back, for transporting 1000 passengers arriving by train onwards with Hyperloop, 25 pods and waiting times up to 50 min would be required. In addition, because of space restrictions, in Hyperloop only hand luggage could be admitted, and, for reasons of efficiency, seats need to be pre-allocated to passengers, requiring check-in as with aviation and the related loss of time.

The development of a novel transportation system with many new features naturally requires considerable, in particular financial means – for this reason, Hyperloop marketing uses as number of slogans intended to impress investors:

- „A fifth mode of transport“ (after water ways, aviation, road, and rail)
- “Energy self-sufficient” (E. Musk has proposed to clad the exterior walls of the Hyperloop tubes with solar panels, possibly supplemented by wind energy)
- “Fast and cheap – for people and goods” (E. Musk)
- “Be anywhere, move everything, connect everyone” (Hyperloop One)
- “Broadband for transport” (Hyperloop One)
- „Airline speed at the price of a bus ticket“ (Hyperloop One)
- „On demand, energy efficient, safe“ (Hyperloop One)
- „Avoids level crossings and collisions with wild animals“ (Hyperloop One)
- „Avoids human errors and bad weather“ (Hyperloop One)
- „Smooth as a ride with an elevator – no turbulences“ (Hyperloop One)
- „Hyperloop is a metro system“ (Hyperloop TT)
- „Hyperloop will change our way to live and to work“ (Hyperloop TT)
- „We have a safer system than railways“ (Hyperloop TT)

As we could see from the description in this section, the fundamental problems with Hyperloop are the comparatively low transport capacity, and, in addition, the structural problem that with Hyperloop it is not possible to build organically growing networks, but isolated lines, and that integration with other modes of transport is not very attractive.

5. Innovation and Development Needs for Hyperloop

Complex transports systems such as Hyperloop, consisting of many individual components, raise the question how the learning curve will be managed in those areas that show a high degree of novelty. For comparison, please note that autonomous driving on roads relies essentially on additional components to an otherwise established system – propulsion, brakes, carbody, air condition, etc. remain the same as with a conventional car. Hyperloop, on the contrary, needs new development or further development in almost all subsystems (see Table 6).

	Vehicles			Infrastructure					Control
	Body + interiors	Air supply, Life support	Propulsion/ Braking	Tube + vacuum	Guidance and suspension System	Safety/ Life Support/ Evacuation	Entry/ Exit	Feeder/ Offload	Including location services
Hyperloop	Could be based on aviation	Based on aviation	Could be based on Maglev, LIMs	From pipelines, vacuum + doors	Could be based on Maglev	From submarines?	Air lock	(for increasing capacity)	to be developed
Hi-Speed Train	existing	n/a	existing	(rail)	(the rail)	n/a	n/a	n/a	existing
Maglev	existing	n/a	existing	(guideway)	existing	n/a	n/a	n/a	existing
Aérotrain	existed	n/a	From aviation	(guideway)	(guideway)	n/a	n/a	n/a	

Table 6: Innovation needs in technical subsystems of Hyperloop

Historical evidence has it that development of complex transport systems usually takes considerable time until sufficient maturity for commercial operation can be achieved. The French high-speed train TGV was already proposed in the 1960s, whereas commercial operation on the stretch between Paris and Lyon was finally started in 1981.

In this context, an interesting parallel development needs to be mentioned, the Aérotrain [7], a hovercraft vehicle with jet propulsion, which had been in serious competition with the TGV concept. Like the TGV, Aérotrain was conceived in the 1960s, by 1969 even an 18 km long test track had been built near Orléans. The vehicles (empty mass 11,25 t) could carry 80 passengers and reached a speed of 430 km/h. That TGV could beat Aérotrain by a convincing margin is in particular due to the fact that from the very beginning TGV trains could run on conventional tracks, meaning TGV could be well integrated with a functioning network, and the TGV network over the years could be expanded step by step.

Maglev systems such as the Transrapid are the result of a decades long development as well (e.g. the test facility in Emsland which was shut down in 2012 was planned in 1969). However, so far, such system could not beat the high-speed train system.

6. The Challenges for Hyperloop

Starting with general aspects it should first be noted that one of the major challenges for Hyperloop is the time still needed to reach product maturity. Considering the analogy to high-speed trains or to Maglev, the development time can be estimated to be at least 20 years – meaning, the first Hyperloop line in commercial operation should be expected for 2033 at the earliest. By this time, however, the transport market will be completely transformed by the advent of electrical autonomous automobiles.

An additional difficulty is that usual methods for risk reduction, namely progressing by smaller steps, are not realistic because of the characteristic properties of Hyperloop. The risk profiles and the long financing period prior to expected returns might discourage potential investors.

There are numerous technical challenges still to be mastered – tests and demonstrations carried out so far have not reached the necessary parameters by a long distance (the maximum speed that has been reached in the course of the Hyperloop pod competition 2017 on a 1,6 km test track is 323 km/h [6]. Acceleration of Hyperloop pods to 1200 km/h needs propulsion systems that are not yet state of the art. More serious appears to be the problem of safe braking of the vehicles, together with the corresponding safe dissipation of the braking energy. Various supply systems in the vehicle

to be provided for emergency situations need energy and weight, thereby reducing potential payload.

In order to guarantee reliable operation, the near vacuum in the tube needs to be maintained over long distances. Because of the extensive loading and offloading systems, Hyperloop stations will require considerable space. The significant wayside infrastructure (with restricted possibilities for branching and intermediary stations) will make it difficult to react to changes in demand for certain travel connections (bus and air traffic are much more flexible here).

In order to contain the equipment costs in reasonable dimensions, cross-project standardisation would be desirable. In addition, transportation companies usually dislike to be locked-in with a single supplier – interoperability of subsystems could be of advantage here.

Like all transportation systems Hyperloop will require authority approval for passenger operation – corresponding authorisation procedures hence need to be developed.

7. Summary and Outlook

Hyperloop on the one hand, is still facing a number of technical and process challenges, on the other hand, there are several system-immanent disadvantages. In principle, every successful innovation needs a positive feedback loop (“success breeds success”). At this time, Hyperloop is still far from such positive feedback: the system design is not yet stable, key concepts (such as braking to standstill) are not yet tested, cost estimates have no solid justification.

Conclusive tests would require rather long test lines (up to 50 km length, in order to reach the full target speed), on top, Hyperloop does not scale well. Despite the significant technical challenges the main problem could be with economy. As shown above, Hyperloop does not bring any advantages in terms of travel time over short distances (50 – 100 km), at considerably lower transport capacity than conventional, already existing systems. Intermediary stations and branches are difficult to implement – this lack of networking capability will be a disadvantage on middle distances (up to about 500 km), in particular where a railway line already exists. On longer routes (1000 km and more) the high fixed cost, together with the lack of flexibility, might be blocking, above all: as long as the concept is not proven in practice, nobody will invest into several hundreds of kilometers of tube, and, as long as there is no sufficient market behind, nobody will invest in the “mass production” of Hyperloop components.

Here, a comparison with the hypersonic aircraft “Concorde” is telling – similar as expected for Hyperloop, this futuristic flight device targeted a drastic reduction of flight times. For the leg London – New York the flight with Concorde took 3h 20 min, whereas a conventional aircraft needed 8 h. Nonetheless, after 15 years of development and 27 years of commercial operation, in 2003 Concorde was taken out of commercial service. The reason: high costs for operation and maintenance, and the restriction to a very small number of flight routes (for reasons of environmental protection). However, the sheer number of essential contributions by Concorde to the development of aviation technology cannot be estimated high enough.

In summary it does not appear nonsensical that Hyperloop will possibly not kill traditional railway systems. Apart from a few niches, not many applications of Hyperloop based transportation systems should be expected. The open innovation approach pursued by Hyperloop, however, can be inspiring for other transport modes. The abundant marketing activities related to Hyperloop will certainly contribute to a renewed interest in questions of transport technology and transport policy. Elon Musk has managed in all his initiatives to create a culture that values highly experimentation, rapid

learning, and incremental improvement. It is especially remarkable with Hyperloop, how a world-wide network of experts and enthusiasts are engaged for a difficult challenge.

8. Literature

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